A SYSTEMS-LEVEL ANALYSIS OF THE JHU/APL TIME AND FREQUENCY LABORATORY

Mihran Miranian, Gregory L. Weaver, Richard Dragonette, and Matthew J. Reinhart
JHU/Applied Physics Laboratory, Laurel, MD, USA
E-mail: *mihran.miranian@jhuapl.edu*

Abstract

In past years, we have reported on continuous improvement in the operation of the master clock of our Time and Frequency Laboratory at the Johns Hopkins University Applied Physics Laboratory. We have discussed our ensemble of hydrogen maser and cesium beam atomic frequency standards into an autonomous timescale that maintains UTC (JHU/APL) within ± 20 ns per month of UTC. This year, since completing the major aspects of our laboratory refurbishment, we have undertaken systems analysis toward optimization and improved timekeeping. In our paper, we will describe the system of clocks, control mechanisms, and their relationship that maintain our laboratory's accuracy. One outcome will describe the determination of our worst performing clock through frequency characterization and the performance improvement in the UTC (JHU/APL) timescale through selectively weighting its contribution.

I. INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has been continuously operating a time and frequency standards laboratory since 1959 in support of a variety of military and civilian projects. The lab was first established to support the Transit Satellite Navigation program, which became operational in 1963. The primary purpose of our lab, then and now, is to provide time and frequency reference signals for our satellite tracking stations, satellite mission operations centers, precision oscillator development lab, and equipment used for acceptance testing. Our sponsors require acceptance test traceability to NIST or USNO, but we also elected to participate in the international community of labs contributing to the TAI with the Bureau International des Poids et Measures (BIPM) in 1978.

Over the last several years, JHU/APL expanded its budget for the Time and Frequency Laboratory (T&F Lab) to support the purchase and maintenance of laboratory grade atomic frequency standards (AFSs) and upgrade the laboratory facilities with sufficient capability to achieve our ± 20 ns accuracy goal to UTC **[1].** To better meet this goal, we established an autonomous timescale algorithm to monitor our clock ensemble and aid in the prediction of UTC (APL) used in frequency steering the microphase stepper that provides the master clock output **[2].** We routinely adjust the microphase stepper more often than the monthly BIPM reporting cycle, so it is important for our timescale algorithm to optimally utilize the clocks of our timekeeping ensemble. The clocks maintained in our laboratory are three cesium-beam atomic frequency standards and four hydrogen masers. However, one hydrogen maser (an aging NASA Research Maser) is not included in the APL Timescale.

With only six clocks in the ensemble contributing to the APL Timescale, we lack the statistical basis for a sophisticated weighting system. Consequently, we have chosen to operate an equally partitioned

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14. ABSTRACT
In past years, we have reported on continuous improvement in the operation of the master clock of our Time and Frequency Laboratory at the Johns Hopkins University Applied Physics Laboratory. We have discussed our ensemble of hydrogen maser and cesium beam atomic frequency standards into an autonomous timescale that maintains UTC (JHU/APL) within ? 20 ns per month of UTC. This year, since completing the major aspects of our laboratory refurbishment, we have undertaken systems analysis toward optimization and improved timekeeping. In our paper, we will describe the system of clocks, control mechanisms, and their relationship that maintain our laboratory?s accuracy. One outcome will describe the determination of our worst performing clock through frequency characterization and the performance improvement in the UTC (JHU/APL) timescale through selectively weighting its contribution.

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weighting system, which is attractive from a simplicity point of view, but does not take advantage of the better performing clocks. Furthermore, we have found the APL Timescale is susceptible to degradation by a poorly performing individual clock. With six independent clocks, we have sufficient observability to estimate each clock's performance and identify significant differences. The unfortunate reality is the discovery that one hydrogen maser is operating in specification, but has a drift component of $\sim 7 \cdot 10^{-14}$ per 1000 hours, nearly six times greater than the other five constituent ensemble clocks. This paper will review our timekeeping operations, elaborate on the evaluation of individual clock performance, and discuss efforts made to improve the performance of our master clock output.

II. UTC (APL) AND THE APL TIMESCALE

Fig. 1 is a flow diagram of the JHU/APL timekeeping system. The APL Timescale ensemble consists of three high-performance cesium and three hydrogen masers. Simultaneous once-per-second measurements of each clock are made and stored, but only hourly measurements are used to formulate the APL Timescale. All clock measurements are referenced to UTC (APL), which is the output of a microphase stepper driven by one of the cesium AFSs. Therefore, the measurements reflect the variations in UTC (APL) as it is steered to UTC. Similarly, the characterized constituent clocks of the ensemble also reflect the variations in UTC (APL) and, as a result, the APL Timescale is referenced to UTC (APL). As a safeguard monitor, daily GPS common-view time transfer data are compared between the U.S. Naval Observatory (USNO) and the National Institute of Standards and Technology (NIST) to alert for imminent inaccuracy. Adjustments to the microphase stepper are made manually from the 30-day prediction of UTC (APL) based on the updated APL Timescale and the monthly BIPM reports of UTC – UTC (APL).

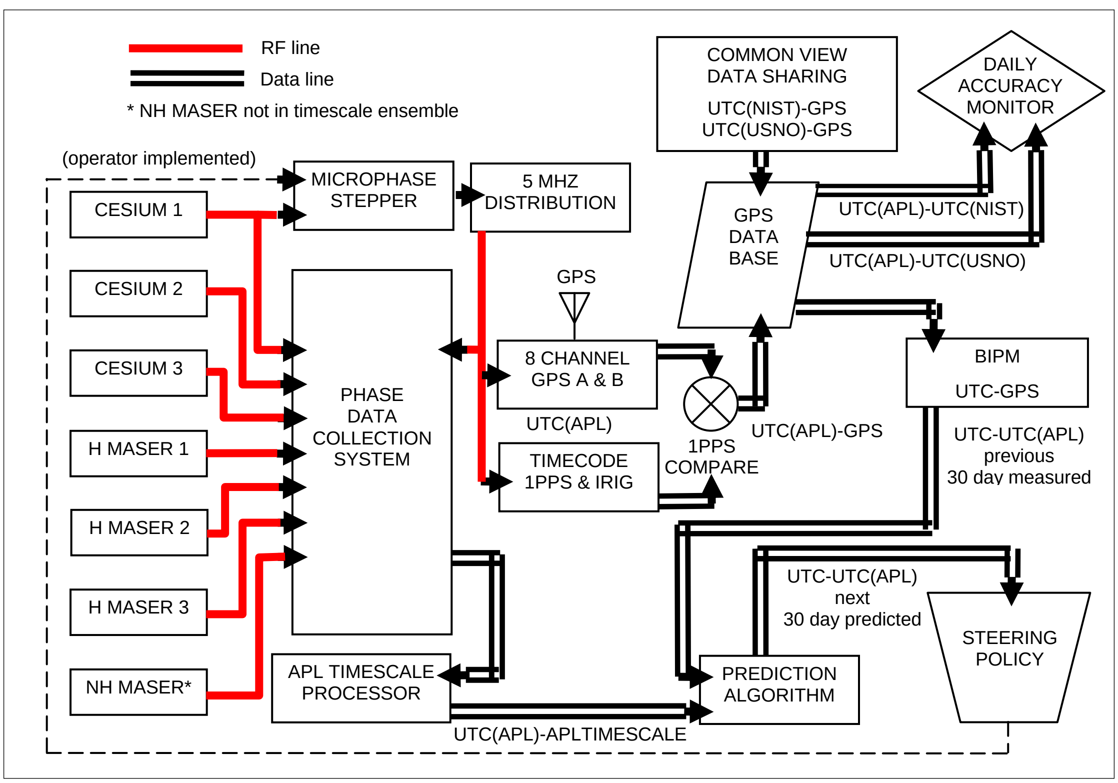

Figure 1. Flow diagram of JHU/APL timekeeping system for UTC (APL)

Fig. 2 shows the accuracy of UTC (APL) to UTC for 100 days, starting at MJD 54310, showing five manual frequency adjustments made to steer and maintain ± 20 ns accuracy to UTC. The red data plot is the leading 30-day UTC (APL) prediction, while the green data are the BIPM actual monthly measurements.

The APL Timescale algorithm is an autonomous process using the current and two preceding days of frequency data for each clock to produce a next day prediction of the timescale. Simply stated, the timescale is propagated 1 day by the previous 3 days of clock characterization. The time interval of 3 days for the autonomous algorithm was set through an optimization procedure that iterated this value from 2 to 10 days and compared the aggregate error of the ensemble clocks' syntonization or error in rate against the APL timescale. It is likely that 3 days emerged as the best value, since this is where the short-term stability of the masers is in best contrast with the frequency stability of the cesium AFSs.

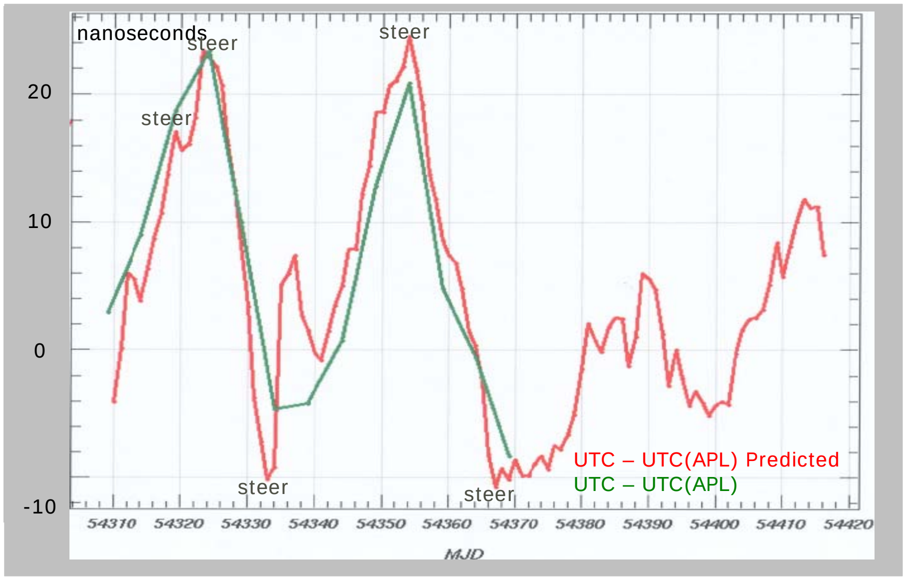

Figure 2. Accuracy of UTC (APL), 30-day leading prediction in red and actual as reported by BIPM in green.

III. ANALYSIS OF APL TIMESCALE AND ENSEMBLE CLOCK SYSTEM

Since 2001, the JHU/APL T&F Lab has undergone continuous improvement by the introduction of new AFSs and timekeeping system upgrades. In late 2006, we reached an operation milestone in which all of our major hardware and software initiatives were in place and contributing well to our timekeeping accuracy. To continue our approach toward improved accuracy to UTC, we performed a system-level analysis of the individual clock performance, their characterization within the APL Timescale, and the contribution to error in the maintenance of UTC (APL). Overall, we had good confidence in the design of the timekeeping system, as shown in Fig. 1, through the daily monitoring of GPS common-view time transfer with the USNO and NIST and the performance to the BIPM monthly reports. We believed that these independent measurements, fed back into our timekeeping system, were sufficient to maintain control. However, we were surprised to discover a residual drift of about 0.025ns/day^2 when we performed a 300-day comparison of the APL Timescale to UTC (APL). This amount of small residual

drift not only appeared in the UTC (APL) – APL Timescale, but also equally in each of the six characterized (syntonized) clocks of the ensemble. We suspected that the drift was likely caused by one or more of the hydrogen masers, as they are more likely to incur long-term drift than the cesium AFSs. In fact, it was known that hydrogen maser #2 had a significant drift, yet in the APL timekeeping system design, it was decided to equally weight each constituent clock as it appeared, from UTC (APL) performance, that the process could successfully characterize the frequencies and drifts of the six clocks and form a sufficiently stable timescale.

Upon discovering the uniform frequency drift for all of the characterized clock data from the equally weighted APL Timescale, a comparison of the raw (uncharacterized) data for each of the six clocks was made against UTC (APL) and prominently revealed that the drift of maser #2 was far greater than the other five ensemble clocks. The first column of Table 1 is a summary of the results from this raw clock data analysis. As stated earlier, and can be seen in the second column of Table 1, the timescale drift error of about 0.025 ns/day^2 appears nearly equal across all of the characterized clocks. Moreover, the uncharacterized clock drift of maser #2 of 0.185 ns/day^2 seems to have been distributed evenly among each of the six clocks and the APL Timescale. Therefore, it was decided to deweight the uncharacterized clock data of maser #2 by a factor of ten and recompute the APL Timescale. The third column of Table 1 shows the results of the selectively weighted APL Timescale and the residual drift errors for each of the six ensemble clocks. By deweighting maser #2, we were able to effectively remove the residual drift from the APL Timescale.

Table 1. Comparative clock drift residuals to UTC (APL) over 300 days.

		Equally Weighted	Selectively Weighted
Clock	UTC(APL) - CLOCK drift in ns/day^2	UTC(APL) - Char. CLK drift in ns/day^2	UTC(APL) - Char. CLK drift in ns/day^2
Cesium 1	0.001	0.024	0.001
Cesium 2	-0.011	0.024	0.001
Cesium 3	0.000	0.024	0.001
Maser 1	-0.009	0.029	0.000
Maser 2	0.185	0.026	0.003
Maser 3	0.011	0.024	0.001
APL Timescale	-	0.025	0.001

Fig. 3 shows the effect of selectively deweighting the contribution of maser #2 from the calculation of the APL Timescale over a 300-day history of data, starting at MJD 54100. This is the same 300-day period used in the residual drift analysis described in Table 1. The red time plot is the difference of the equally weighted APL Timescale and UTC (APL) and the green time plot is the selectively weighted APL Timescale against UTC (APL). In both cases, the first-order slope (frequency offset error) has been removed. The drift of the equally weighted APL Timescale is clearly evident in the red time plot as a second-order component, while the selectively weighted APL Timescale shows no obvious drift component. Notice that the frequency noise terms have remained constant between timescale plots, indicating the removal of drift rather than filtering.

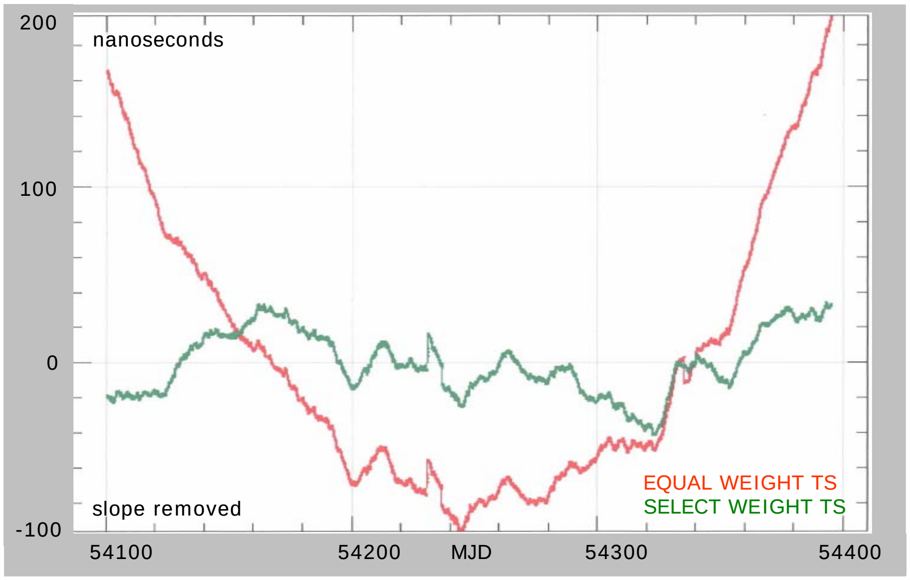

Figure 3. Comparison of equally weighted and selectively weighted APL Timescales against UTC (APL).

As a final aspect to the analysis, we determined the individual frequency stability of each of the ensemble clocks through the use of the three-way comparison method. Described previously in numerous papers, the Allan deviation of three unique sets of two clock comparisons (A-B, A-C, and B-C) can be used with three mostly similar sources to estimate their individual performances **[3]**. We first chose to compare the three maser set and then the three cesium AFSs set to maintain the mostly similar source constraint. This decision worked well for the cesium AFSs set and up to about 250 hours for the masers, where the drift of maser #2 then became to large to effectively determine the other two masers. Consequently, a third set of two-way comparisons was created using cesium AFS #3 with masers #1 and #3. Fig. 4 shows the results of these three-way comparison sets in determining the individual stabilities for each clock in the APL Timescale ensemble.

The frequency stability plots shown in Fig. 4 offer several interesting insights to our timekeeping system beyond the previously determined large drift aspect of maser #2 compared to the other five clocks. The frequency stability of cesium AFS #2 has a prominent hump in its long-term character at 250 to 1000 hours. Usually a hump aspect in the Allan deviation character of a source is associated with incidental spurious sidebands or actual frequency modulation of the source. Given the long-term nature of the frequency stability anomaly of cesium #2, we suspect its association to laboratory environment such as temperature or humidity change. However, since the other two cesium AFSs do not show similar aspects, this could mean an unusual sensitivity, a very local gradient, or an emerging intrinsic problem with cesium #2. In any event, we will pursue to determine a cause in our ongoing work.

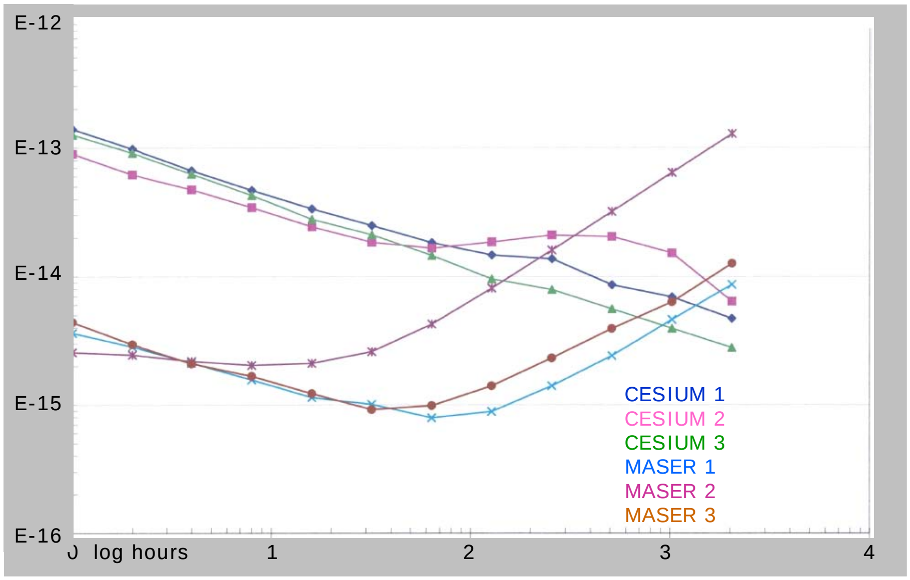

Figure 4. Individual Allan deviation performance for the six APL Timescale clocks.

Another overall insight is our choice of mixing an equal distribution of hydrogen masers and cesium AFSs into the APL Timescale ensemble does yield the desired advantage of using excellent short-term against the long-term stability character of dissimilar clocks to more effectively maintain timekeeping with as short of an error-determining cycle (integrating time interval) as possible. As noted earlier, it can be seen that, for our APL timescale, the lowest residual error across all six clocks appears about the 32- to 64-hour time interval region. Finally, although the autonomous timescale algorithm can effectively homogenize the character of the clocks over its 3-day cycle, we are reminded that measuring and analyzing the individual frequency stability of each clock on a routine basis is prudent for timekeeping facilities dependent on a small number of clocks to provide assurance against intrinsic or external changes that could ultimately degrade our final UTC (APL) product capability from its ± 20 ns accuracy goal.

IV. APL T&F FACILITIES IMPLEMENTATION AND COMPROMISES

As noted in the Introduction, the JHU/APL T&F Lab mission remains to provide high-quality timing signals sufficient to support the many JHU/APL projects and programs that require precise time and frequency. However, the scope of this mission is limited to sufficient stability and has led to budgetary compromises in the implementation of the T&F lab facilities. For example, since we continue to provide signals of more than sufficient stability without an extensive environmentally controlled room facility or individual temperature chambers to maintain the masers, the T&F Lab budget has been limited from implementing the addition of this capability.

To control the equipment heat load and, therefore, the temperature environment for the ensemble clocks, a dedicated air conditioning (A/C) system was installed into the T&F Lab facility. The dedicated A/C system has limited capacity, so it is augmented from the building distributed heating/cooling. Originally the T&F Lab facility A/C was configured to maintain the temperature to 68 ± 1 ^{o}F. While optimal for the T&F equipment, this led to a nearly constant series of short on/off cycles for the A/C compressor. After replacing the compressor for the third time in 5 years, the system was reset for 68 ± 3 ^{o}F. This opening of

the temperature control limit has not affected the quality of the T&F lab distributed timekeeping signals sufficiently to be noticed by our users, and we have held off compressor issues for a few years.

To provide as stable an environment as we could for most of the T&F Lab equipment (except the four masers, which are stand-alone), we added duct work to force cooled air directly from the room A/C into the seven equipment racks maintained by the T&F Lab. Air is forced in through the bottom of the racks, and out through vents in the top of the racks and through the small spaces between devices mounted in the racks. This air-channeling arrangement provides the environment for the three cesium AFSs.

Historically, there has been no humidity control in the standard laboratory type room in which the T&F lab is located. This uncontrolled humidity, combined with the dehumidification provided by the T&F facility A/C, produced relative humidity levels well below 40% during air conditioning season, and below 20% during heating season. Recently, the laboratories immediately adjacent to the T&F lab have added humidity control and over the past 6 months, we have seen the humidity rise to above 50% in the T&F lab. The facility A/C dehumidifies the room when the relative humidity rises above 60%. As a result, over the past 6 months, the relative humidity in the T&F lab has varied from 50% – 60%. It will be interesting to see what measurable effects this recent change has on system-wide performance.

The frequency stability results shown in Fig. 4 for the individual ensemble clocks prompt us to look deeper as to whether the environmental arrangements in the T&F lab may be influencing our timekeeping system performance. Specifically, the ducted cooling arrangement for cesium #2, while similar to cesium #1 and #3, is located in a different rack segment. Also, the lack of circulation return to the primary building ventilation could be inducing variable air pressure gradients. In the near future, we plan to experiment with cesium #2 by removing it from its rack location, allowing it to freely dissipate its heat to the laboratory environment.

With respect to maser #2, it is well known that temperature sensitivity is a primary concern in hydrogen maser stability. However, our examination shows that the drift rate seems stationary for nearly 600 days with no evidence of periodicity; so we are less inclined to disturb its location.

V. SUMMARY AND PATH FORWARD

Our system-level analysis of the JHU/APL timekeeping system yielded important findings that should benefit the capability of our maintenance of UTC (APL) to within ± 20 ns of UTC. Most significantly, we discovered that the autonomous timescale did not sufficiently characterize the significant drift of hydrogen maser #2, imparting a drift to the equally weighted APL Timescale. We effectively mitigated this problem by deweighting the contribution of maser #2 by a factor of ten in a selectively weighted version of the APL Timescale. Although we have been operating on the selectively weighted APL Timescale since MJD 54370, we are not satisfied with this tactic as a solution, since it reduces the statistical moment of our small number clock ensemble, places greater dependency on the reliability of the remaining five clocks, and essentially discounts the JHU/APL investment associated with the purchase of the maser. Therefore, we are now considering alternatives toward a path-forward strategy to be pursued in the next year.

There remains a possibility that the drift of maser #2, if intrinsic, might be adjusted through the servo auto-tuning feature, though the maser manufacturer has not provided confidence that this will result in any benefit. The discovery of a hump in the frequency stability of cesium AFS #2 offers suspicion for environmental issues in the T&F facility and, though maser #2 is not in proximity to cesium #2, justifies some pursuit of local gradients affecting both clocks stability. Careful experimentation with the location

of maser #2 and cesium AFS #2 within the facility could prove rewarding. Another approach for removing the drift from maser #2 is to pre-condition its data prior to contributing to timescale generation. This would require the drift character of maser #2 to be mostly stationary and the use of some other reference other than the APL Timescale, perhaps masers #1 and #3, to properly act on the data. Finally, there is the purchase of more clocks for the facility. However, with no vendor assurance that the clocks purchased would prove beneficial to the stability already achieved with APL (UTC), we hesitate to exercise this option unless faced with and end of life situation sometime in the future.

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